

Antimatter Gravity and Antihydrogen Production¹

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ABSTRACT

Certain modern theories of gravity predict that antimatter will fall differently than matter in the Earth's gravitational field. However, no experimental tests of gravity on antimatter exist and all conclusions drawn from experiments on matter depend, at some level, on a specific model. We have proposed a direct measurement that would compare the gravitational acceleration of antiprotons to that of negatively charged hydrogen ions. Substantial progress towards the development of this experiment has been achieved. Based on our work a number of alternative proposals for measuring “ g ” on both charged and neutral antimatter have been made. We summarize the present

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status of our experiment and also discuss the steps that would be necessary to produce antihydrogen in an environment suitable for gravity measurements.

1 Introduction

An area of experimental physics which needs attention is the study of the gravitational acceleration of antimatter compared to that of matter. A number of attempts to unify gravity with the electro-weak and strong interactions call into question the general belief that the results should be identical. However, no experimental tests have been performed [1].

We have proposed an experiment to study gravity on antiprotons [2] and this experiment is in progress at LEAR/CERN in Geneva, Switzerland. Two main technical problems can be identified in this proposal. Firstly, one needs a sufficiently large number of ultra-cold antiprotons to obtain a statistically significant result. Secondly, electromagnetic forces acting on the charged particles need to be reduced to an extremely low level. To make the force of gravity observable one must reduce electric fields to a level well below 10^{-7} V/m in the critical portion of the experimental set-up. (One must also minimize any magnetic gradient fields). Such a reduction seems possible, but very difficult. This difficulty has prompted alternative proposals to utilize a neutral particle, specifically the antihydrogen atom. Both these approaches are being pursued and are covered by this work.

The ballistic “Galileo” method to measure gravity on antiprotons is described in detail in reference [3]. It uses the idea originated by Witteborn and Fairbank [4] to measure the gravitational acceleration of electrons. One launches a large number of ultra-slow particles upwards against the gravitational force and measures the time-of-flight for each individual particle. The resulting time-of-flight distribution will exhibit a cut-off time representing the fact that particles below a certain initial kinetic energy cannot climb up to the height of the detector. A simple calculation shows that this cut-off time “ τ ” is directly dependent on the gravitational acceleration “ g ” and on the geometrical length “ L ” of the experiment, but does not depend on the intrinsic kinematic parameters of the particle sample:

$$\tau = \sqrt{L/2g} . \tag{1}$$

The plan using a neutral particle would proceed via the production of a composite particle, the antihydrogen atom, consisting of an antiproton and a positron. To measure gravity (as well as to provide the opportunity of precision spectroscopy for CPT tests at unprecedented levels of accuracy)

would require these antihydrogen atoms to have extremely low kinetic energies and they would preferably also be confined in a small volume in space (in a trap configuration). Two proposals to achieve this have been discussed.

The first approach uses a recombination process between antiprotons in a Penning trap and a dense positron plasma. (We will discuss it in Sec. 4.1). The second method, under consideration by our collaboration, is a charge-exchange reaction between antiprotons and positronium atoms. Even with a reduced production rate there are advantages to this approach. The cross section exhibits a broad maximum over an energy range from 0 to 20 keV, so in principle the antiprotons do not have to be ultra cold. More importantly, antihydrogen is produced directly in the ground state and low-lying excited states. Therefore, the system is not as susceptible to field ionization as the high- n states produced with the first method and is furthermore directly accessible to spectroscopic measurements. Specific states can be preferentially populated using excited positronium states, which also increases the reaction rate by the fourth power of the principal quantum number, n , of the positronium atoms.

The following lays out our basic experimental approach and describes the progress made to date.

2 Capture and cooling of antiprotons

An important prerequisite for both the gravity measurement on antiprotons and also the production of antihydrogen is a sufficient supply of cold antiprotons. Antiprotons are produced in high-energy collisions, and are typically injected into large accumulator rings (at CERN and Fermilab) to be used in high-energy physics experiment. At CERN, a portion of the antiprotons is transferred to a low-energy antiproton ring (LEAR), where they are made available to physics users at energies as low as 5.9 MeV. To achieve the extremely low energies necessary for the work discussed here, approximately 10 orders of magnitude have to be bridged with an efficiency of a few tenths of a percent or better.

We have developed a method based on a combination of energy loss in material and electrodynamical capture of charged particles in a Penning trap (which is a superposition of a strong homogeneous magnetic field and an electrical quadrupole field). 5.9 MeV particles are passed through a thin

target foil and, with a proper choice of target thickness, up to 5 percent of the antiprotons emerge from the down-stream side of the target at energies below 50 keV. These “low-energy antiprotons” are dynamically captured in our large “catching” Penning trap. This is done by rapidly switching the electrical potential on the electrodes once the beam pulse from the accelerator has fully emerged from the target. In our set-up at LEAR we have demonstrated the direct capture of up to one million antiprotons in a trap specifically designed to match the LEAR output phase space. Once captured, these antiprotons are cooled by interaction with cold electrons (which have been preloaded into the trap and have cooled by synchrotron radiation before the beam pulse arrives).

Recently we have demonstrated the successful collection of 60 percent of the initially captured antiprotons into a small, harmonic region of our large trap at energies below 1 eV. Surprisingly, the observed storage time of the cold antiprotons in this trap was in excess of one hour, even though the residual gas pressure was as high as 10^{-11} Torr. In these runs the annihilation of the antiprotons on the residual gas molecules was monitored with external scintillators. After an initial cool down period, no annihilation signals were seen above the background cosmic-ray events, even though a significant number of antiprotons was still present in the trap at the time of release one hour after capture [5]. This enables us to now consider the next stages of experimentation, both with charged antiprotons and neutral antihydrogen.

3 The Antiproton Gravity Experiment

The principle of the proposed method to measure the gravitational acceleration of antiprotons was pioneered in a challenging experiment performed at Stanford University in the 60’s [4]. The authors of this experiment reported a zero net force on free electrons traversing a vertical shield tube. This result was explained by the fact that the free electron gas in the metal tube (used to shield external electric fields) sagged under the influence of gravity. Thereby an electric field was produced which counteracted the force of gravity. To do this measurement, stray electric fields from variations in the work function along the inside surface of the shield tube (the Patch effect) had to be below 10^{-11} V/m.

In the experiment proposed here the requirements on reducing the field

inside the tube can be relaxed by three orders of magnitude due to the inertial mass of the antiproton being 2000 times larger than the electron mass. Even so, to minimize the electric fields on the central axis of a cylinder due to patches with differing work functions along the surface of the inside wall of the cylinder, we have conducted a series of systematic studies to minimize the variation in work function from patch to patch as well as the size of the individual patches.

Patch sizes can either be dominated by the intrinsic structure of the material or by substances that adsorb on the surface. For these reasons it became apparent that an amorphous, non-reactive, single component (no alloys) material is the best choice. We have used a vibrating capacitive probe (Kelvin probe) to study small samples of different surfaces and have identified two candidates: graphite in the form of an aerosol spray (Aerodag) and ultra-thin layers of gold on a germanium sub-layer [6]. Both these surfaces do not exhibit any work function variations at the level of the instrument resolution of the Kelvin probe, 1 mV. But the observed changes in overall work function when using graphite samples with different degrees of orientational disorder may point towards work function variations not too far below the resolution limit [7]. Such an effect is not expected for the gold/germanium surfaces. Work in this area is now continuing at our collaborating institution in Genova, Italy, with an improved instrumental set-up. Here a probe with a much larger area will be used, allowing us to study large-scale variations of the workfunction [8].

One obvious method to dramatically increase the sensitivity of these studies is to use the time-of-flight method itself as a probe for the surface electric fields present in the system. For this purpose we have constructed a test experiment consisting of an ion source, a drift tube, and a particle detector [9]. Ions are transferred from the ion source to the entrance of the drift tube at 1 - 2 keV energy to minimize the error in the definition of the start time. Here they are retarded by an electric potential to zero mean kinetic energy. Some ions are rejected and others still traverse the drift tube at high energies. With the proper choice of the current density in the pulse from the ion source, a small portion of ions (preferably less than one per pulse) enters the drift tube near zero kinetic energy. These particles are sensitive to the electric field along the tube axis and their time-of-flight will provide a measure of the rms fluctuations of these fields.

In preliminary tests of this system we established an energy spread of

the ion source output of less than 7 eV. This, in conjunction with the output current, would yield a sufficient density of particles in the low-energy bins of interest. But these tests also revealed a high neutral background density from the ion source which is saturating the particle detector during and shortly after the ion pulse is injected, therefore blanking the signal of late arrivals. This prompted us to install a small Penning trap as an intermediate storage unit between the ion source and the drift tube. This trap can dynamically capture more than 10^6 charged particles from the ion source and release them again with a delay sufficiently long to let the neutral background decay away. The installation of this trap is currently under way and first results are expected soon.

4 Antihydrogen formation

4.1 Background

A variety of schemes to produce antihydrogen have been proposed in the literature [10]. Amongst these, only the reactions listed below (with the appropriate references for detailed discussions) will yield the ultra-low energy antihydrogen atoms needed:

$$e^+ + e^+ + \bar{p} \Rightarrow \bar{H} + e^+ + h\nu \quad (2)$$

(see Ref. [11]), and the two reactions

$$Ps + \bar{p} \Rightarrow \bar{H} + e^- + h\nu , \quad (3)$$

$$Ps^* + \bar{p} \Rightarrow \bar{H} + e^- + h\nu . \quad (4)$$

(See References [12]-[14] and [15]-[16], respectively.)

In the first case, both constituents forming antihydrogen need to be trapped. In the last two cases, only antiprotons need to be confined before the recombination process since the positron is delivered in form of a positronium beam. Both methods have distinct advantages and disadvantages and, depending on the final application, either one could be a better choice.

In the first process, the positron density provides a second positron in the vicinity of a collision between antiprotons and positrons to assist in

the conservation of energy and momentum. This makes the rate constant strongly temperature dependent:

$$\Lambda = 6 \times 10^{-12} (4.2/T)^{9/2} n_e^2 s^{-1} . \quad (5)$$

Therefore, the rate benefits vastly from cooling the particles. Because of the mass difference between positrons and antiprotons, with positrons at 4.2 K the antiprotons could have energies as high as 1 eV before the recombination rate is significantly affected. This could be used to form a beam of antihydrogen atoms, at eV energies, leaving the trap in the axial direction. (However, the beam quality would strongly depend on how well the axial energy of the antiprotons could be decoupled from the radial energy.)

While the theoretical production rate for this process appears, at first sight, to be extremely high (with a $10^7/\text{cm}^3$ positrons at 4.2 K one obtains $\Lambda = 6 \times 10^6 \text{ s}^{-1}$), two critical problems have been identified:

Firstly, the antihydrogen atoms are created in an extremely high Rydberg state ($n = 100$ or larger). This gives rise to the possibility that these loosely bound systems are field ionized by the electric field gradients present in the trap, needed to store the antiprotons and positrons prior to recombination. This may partially be the reason that the charge conjugate reaction (protons on electrons producing hydrogen atoms) has not yet been observed in recent attempts [17]. Secondly, the neutral atom traps available for antihydrogen only stabilize specific spin states (low-field seeking states) and a spin change during de-excitation from these high n levels to the ground state must be carefully avoided.

To combat the ionization problem, a mixture of collisional and spontaneous deexcitation might be used, provided the antihydrogen does not drift outside the positron plasma on the same time scale. Alternatively, laser induced de-excitation could be attempted. Additionally, magnetic field effects both on the recombination process and on the survival of the antihydrogen Rydberg atoms need to be studied in detail before a final assessment of the advantages and the disadvantages of this method for a specific application can be made.

Alternatively to the process of Eq.(2), one can enhance the radiative antihydrogen formation rate by several orders of magnitude by coupling the recombination process to a third particle (for energy and momentum conservation) using collisions between positronium atoms and antiprotons

[16]. [See Eqs. (3) and (4).] This process can be interpreted as Auger capture of the positron to the antiproton. Cross sections have been estimated by Humberston, et al. [13], using charge conjugation and time reversal to link the cross section for positronium formation in collisions between positrons and hydrogen to the antihydrogen formation cross sections. Early calculations assumed both antihydrogen and positronium to be in the ground state, resulting in a production cross section of $3.2 \times 10^{-16} \text{ cm}^2$ with a broad maximum at a \bar{p} energy of 2.5 keV. Calculations of the total antihydrogen formation cross section using classical and semi-classical methods [18] have obtained values which are considerably larger than the ground-state results. Values for the formation of antihydrogen in excited states are given by Ermolaev, et al. [19] and indicate that there is a large cross section to low-lying excited states.

4.2 Recombination experiments with protons

To test the validity of the calculated cross-sections, our collaboration has set up an experiment to perform the charge-conjugate experiment of forming hydrogen atoms via collisions between protons and positronium [20]. Besides testing the theoretical predictions for production, this experiment also would allow us to develop the necessary technology of positronium production and handling.

In this experiment a pulsed, low-energy positron beam is made to impinge upon a heated silver target. This acts as a high-vacuum source of positronium (Ps) atoms. An intense proton beam ($100 - 200 \mu\text{A}$ at 9 keV) crosses the Ps target. The production of a hydrogen atom is signaled by the detection of the (low-energy) fragment e^+ in time relation to the initial e^+ pulse.

The initial low-energy e^+ 's are produced using a rare-gas solid moderator bombarded by β^+ particles from a 3 GBq (80 mCi) ^{22}Na radioactive source. The slow e^+ 's are accelerated to 300 eV in the axial confining field of around 10^{-2} Tesla. Using a pair of curved $\mathbf{E} \times \mathbf{B}$ plates, the e^+ 's are also deflected by 25 mm to remove the remainder of the beam line from the direct line-of-sight of the radioactive source. The e^+ 's are then decelerated to 10 eV and passed into a buncher. At this point the d. c. beam has an intensity of around $5 \times 10^6 e^+/\text{s}$. The potential in the one-meter-long buncher varies quadratically and, if switched on, produces a time-focussed

ejected e^+ pulse. Currently the bunching efficiency is approximately 10 %, in good agreement with expectations based upon the 120 ns pulse width and the 100 kHz repetition rate. The width of the positron pulse has been measured to be below 5 ns. Provisions to accumulate positrons in the buncher for a higher-intensity output have been made but not yet tested. The positrons would leave the buncher at a kinetic energy of 7.5 keV and impinge upon a 200 nm Ag(100) foil. There they would be converted with a 10 – 20 % efficiency to low-energy positronium atoms.

The proton beam is brought to a focus about 2 mm in front of the Ag(100) foil to produce the optimum overlap between the positronium and the protons. The fragment e^+ resulting from the production of a hydrogen atom is accelerated by applying 600 V across the 20 mm gap between the Ag foil and the first element of the extraction optics. It is then deflected through two 90° bends, which are finely tuned to allow passage of the e^+ to the channel electron-multiplier array (CEMA) detector. This detector is placed in coincidence with a NaI(Tl) detector to unambiguously identify the e^+ signal.

The individual parts of this experiment have been constructed and tested. Our efforts are now going towards testing the interfacing of these individual components. By using the calculated cross section (6×10^{-16} cm²), beam strengths (5×10^6 e^+ /s and 150 μ A proton current), the production efficiency of Ps in transmission from the heated Ag foil (10 %), the ortho-Ps lifetime (142 ns), and realistic detection and bunching efficiencies, the estimated event rate will be around 10^{-2} /s. This should be clearly distinguishable above the background.

After the conclusion of this experiment, the technologies of producing positrons, injecting them into a target chamber, and converting them to low-energy positronium atoms can be implemented into our trapping experiment at CERN. A detector arrangement consisting of an array of small silicon pads is being designed. This detector array will have enough spatial resolution to be able to discriminate between the pions from antiprotons annihilating on the residual gas in the trap and those resulting from neutral antihydrogen atoms escaping from the electromagnetic confinement of the Penning trap and annihilating on a nearby target.

The first goals of the antihydrogen experiment will be to detect the production of antihydrogen atoms using the positronium-antiproton reaction and to verify that these antihydrogen atoms are stable against the

electric field gradients present in the Penning trap environment. In a second stage of the experiment we propose to detect the Lyman- α radiation from antihydrogen atoms formed directly in the $n=2$ state, thus verifying the population of low-lying states. Once this has been completed, physics experiments with antihydrogen atoms can be considered.

4.3 Possible experiments with antihydrogen

Considering the effort necessary to produce antihydrogen one must naturally ask the question what the physics benefits of such an endeavor would be. In principle, these can be found in two areas: 1) Comparison of results of spectroscopic measurements of hydrogen and antihydrogen, which would constitute a test of CPT at a level rivaling even the result on the kaon system, and 2) the study of the gravitational interaction of antimatter with the Earth's gravitational field, which would test the validity of the weak equivalence principle (WEP) and possibly shed light on the problem of unifying gravity with the three other forces.

Over the last decade, the precision of spectroscopic studies of hydrogen advanced enormously. Today the highest precisions have been achieved for the hyperfine structure (6.4×10^{-13}) and for the $1s$ - $2s$ transition (1.8×10^{-11}). Based on the lifetime of the $2s$ state ($1/8$ second) and the natural linewidth connected to this, a possible precision of 10^{-18} has been theorized. This latter precision would require using trapped hydrogen atoms, an environment which would be directly applicable to antihydrogen.

Currently the best tests of CPT invariance have been performed in the kaon system followed by precision comparisons of the magnetic moments and masses of the electron, positron, proton, and antiproton. The comparison of the inertial masses of the proton and the antiproton have now reached a precision of 1.1×10^{-9} [21]. But in the strict sense, this must be considered only a measurement of the ratio of the charge-to-mass ratios of the two particles. This needs to be combined with the measurement of the Rydberg of protonium to extract an independent CPT test [22]. With the current precision on this quantity [23], a CPT test of only 2×10^{-5} is possible. Using the Rydberg of antihydrogen, one can construct a limit for the charge equality between antiproton and proton which is entirely based on frequency measurements, and could yield a direct test of CPT at the level of 10^{-11} .

Simple ballistic measurements of “ g ” on antihydrogen are difficult and unlikely to yield a very high precision measurement because of the photon recoil limit of approximately 2.4 mK. Consequently, a more elaborate method, using a horizontal beam of ultra-low energy antihydrogen atoms, has recently been suggested [24]. Here the vertical deflection of the beam would be measured using a transmission interferometer. The approach is based on the example of an interferometric measurement of a beam of cold sodium atoms [25] in which the phase of the interference pattern was obtained to 0.1 radian with only 4000 atoms in the beam.

Assuming an antihydrogen beam with a velocity of $v = 10^4$ m/s (which corresponds to a wavelength of 40 pm) and a deflection of 0.8μ m, an uncertainty in the phase measurement of 0.1 radian would lead to an uncertainty in the measurement of “ g ” of 1%. One needs to realize that such an experiment would not require trapping of the antihydrogen atoms and could therefore be considered a first stage experiment comparable to, but not vastly superior to, the ballistic measurement of experiment PS200.

If the formed antihydrogen atoms could be trapped and laser cooled to form an atomic fountain, a potentially much more powerful method could be developed based on the work of by Chu and collaborators [26]. In their experiment they used velocity-sensitive, stimulated Raman transitions to measure the gravitational acceleration, “ g ”, of laser-cooled sodium atoms in an atomic fountain geometry. An ultra-cold beam from an atomic trap was launched upwards and was subjected to three subsequent pulses to drive a two-photon Raman transition between the $F = 1$ and 2 levels in the $^3S_{1/2}$ state. A first $(\pi/2)$ pulse prepared the sample in a superposition of the two states, the second (π) pulse reversed the populations, and the third $(\pi/2)$ pulse brought the wave packets to interference. The interference was detected by probing the number of atoms in state 2.

In the absence of external forces acting on the atoms the final state of an atom will depend on the phase of the driving Raman field. In the frame of reference falling with the atom, the Raman light fields appear linearly Doppler-shifted in time, which shows up as a phase shift varying as the square of the time. Using a 50 ms delay between the pulses, distinct interference fringes were observed, and a least square fit to the data gave an uncertainty in the phase determination of 3×10^{-3} cycles. This represented a sensitivity to “ g ” of $\delta g/g = 3 \times 10^{-8}$.

Despite the enormous advances in the field of hydrogen spectroscopy

over the last years, hydrogen (and certainly antihydrogen) is ill-suited for high precision measurements. A translation of the above method to the case of antihydrogen will not be trivial and straight forward. A large problem will be imposed by the much higher photon recoil limit for laser cooling hydrogen atoms (≈ 3 mK) which gives an rms velocity spread of approximately 700 cm/sec. A much faster fountain beam, resulting in greatly increased experimental dimensions, will have to be used. Therefore, a much larger fraction of the initial beam pulse will be lost due to ballistic spreading during the flight time of the sample. Much less than 1 % of the initial population can be expected to contribute to the fringes. Nevertheless, this method is the only one identifiable in the current literature which shows the potential of a high precision measurement of “ g ” on antihydrogen atoms.

5 Summary

Recent progress in trapping and storing low-energy antiprotons has created exciting opportunities for fundamental research, especially in the areas of CPT violation and gravity. We propose to explore what, in our opinion, is the most promising route to produce antihydrogen in both an intrinsic state and an external environment suitable for high-precision measurements in these areas. Success in this activity could help in convincing the CERN leadership to extend the lifetime of the LEAR program at CERN beyond the current shut-down date at the end of 1996 as well as in convincing other laboratories worldwide (FNAL, BNL, KEK) to add ultra-cold antiprotons to their menu.

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